The Ballantrae Complex

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Introduction

The Ballantrae Complex in SW Ayrshire has attracted a good deal of attention since the last century, when Murchison, Geikie and Bonney discussed its problematical origin. It was clear to most of these and subsequent workers that the association of serpentinite, chert and pillow lavas was repeatedly found in major fracture zones, and for this reason they regarded the association as significant. However, the true importance of the rocks at Ballantrae became more apparent when work in Newfoundland and Cyprus demonstrated that rocks, similar to those found at Ballantrae, were fragments of oceanic crust, and that these oceanic crustal slices had been thrust onto the continents. As the knowledge of destructive and passive margins increased it became clear that the slices of oceanic crust which had been thrust onto continental margins were a signature of typical destructive margins: and so, with the Ballantrae complex in mind, Dewey (1969) recognised for the first time the Caledonides as a destructive margin. The whole rock assemblage at Ballantrae has become increasingly important, not only because it is oceanic crust, but also because its presence here raises a number of important questions, two of which are applicable generally to rocks of this oceanic type (ophiolites).

Firstly, in what kind of oceanic setting did these rocks form ? This entails the establishment of criteria by which various types of oceanic crust can be distinguished.

Secondly, how does oceanic crust appear on land areas, when it appears that most of it is being consumed at trenches?

The excursions which follow this introduction all have a bearing on answering both of these questions.

Origin of ocean crust

Ocean crust is now known to form at two main situations: ocean ridges and marginal basins. However, crust of oceanic type may also form in hot-spots (sea mounts) or in oceanic island arcs. Most of the ocean crust now produced on the earth's surface forms at mid-ocean ridges, and this crust has a characteristic structure (Figure 25.3) which may largely depend upon the rate at which the crust is generated.

When this structure is compared with the rocks at Ballantrae it is clear that, with the possible exception of the sheeted dyke complex, all the rocks which are thought to be characteristic of ocean crust are present; for this reason alone it is fairly safe to assume that the Ballantrae rocks are of oceanic type (Figure 25.4). But there are many types of oceanic crust to consider, and there has been much debate about which of these types of crust is represented by the Ballantrae Complex. The origin of the various types of crust is shown in (Figure 25.5), together with their main characteristics. The most diagnostic characteristic of the various kinds of crust are seen in the layers 1 and 2: differences which might arise in the other layers of oceanic crust are not well known. Where there are faults crossing the hot ridges, deformation and metamorphism may occur whilst the oceanic crust is being formed.

Oceanic ridges are usually found in quite deep water and are characterised by fine grained sediments in layer 1: these are often produced by organisms such as radiolarians living within the water column and falling onto the plate surface after death. As there is little explosive activity at these depths this fine grained sediment is usually devoid of much tuff. Black shale-type deposits may comprise layer 1, where the ocean floor in near a source of terrestrial sediment, as for example, where ocean crust reaches a subduction zone.

Layer 2, usually comprises basalts with a minor amount of breccia and very little evidence of explosive activity during the formation of the lavas–the water being so deep that the water pressure is too high to permit much explosive release of gas. These lavas are often pillowed but do not extend for great distances since there are low slopes at most of the positions of extrusion on the ridge and the lavas tend to chill quickly. This results in mounds of pillows locally building over the points of extrusion.

With the development of hot-spots and seamounts on the ocean plate the nature and thickness of the lava pile is changed. In this instance the lava pile grows from deep water to shallow, so that initially the pile is dominated by pillows which lack evidence of explosive activity, to be followed at the top of the pile by a relatively thin interval of shallow water and intertidal flows and finally the subaerial flows as the cone emerges to form an island (Figure 25.5)B. As these lavas are built on ocean crust which was generated at a ridge, the age of the lavas will be much younger than the age of the ocean crust, provided they formed at some distance from the ridge; and, conversely, the ages of the two will be similar if the hot spot is close to a ridge.

Marginal basins are far more complex, and whilst there are apparently many ways in which they are produced, a common way is to rift an arc to produce new oceanic crust within the rift zone (Figure 25.6). The new oceanic crust may then grow in the usual way to create a new marginal basin terminated on the continent side by a remnant arc (RA, (Figure 25.6)), and on the ocean side by the now rejuvenated active arc (Figure 25.6). In this way there can be stretches of oceanic crust belonging to marginal basins which are divided by remnant half-arcs.

The sequences produced by this means are quite different from those produced elsewhere. Layer 1 is not now a sequence of fine grained sediments produced some distance away from source, but coarse detritus derived locally from the splitting arc (CS (Figure 25.6)B); however, as the marginal basin opens up so the sources become more distant and the sediment finer grained (FS (Figure 25.6)B). During the splitting of the arc, the foundation upon which some of the sediment has already accumulated becomes unstable and subject to extensional faulting. There are now sharp boundaries between sources and basins. The volcanogenic sediment, which accumulates as an apron around the arc, is made up of angular and (intertidally) well rounded clasts, and is displaced into deeper water as mass flows. Sediments, some of which come from the shallow-water zones are displaced towards the basin axis by slump and mass flow action. Finer grained sediment may be organically produced (e.g.cherts) in association with wind blown ash generated by explosive activity on the arc.

The arc itself comprises a great thickness of volcanogenic sediment and, to a lesser extent, lava. If the arc has been allowed to develop for a long time it becomes mature and produces acidic lavas. If, however, it is continuously rejuvenated, as when it splits to form a new marginal basin, then the arc may remain immature and produce basic lavas only. In this arc regime the volcanogenic sediments range from being subaerial to shallow water intertidal to deeper water.

There are a few critical features of the Ballantrae complex which have some bearing on the type of ocean process which might have formed it. These are as follows:

1. Cherts and black shales occur in a number of associations at Ballantrae and in terms of oceanic layering can be ascribed to layer 1 (Figure 25.3). As discussed above, of special importance are:

(a). The presence or absence of coarse grained clastic sediments; deep ocean basins are dominated by fine sediments; parts of seamounts and all of island arcs are dominated by coarse sediment (Figure 25.5). The sediments of layer 1 can be seen at Bennane Head where they are found in association with boulder-bearing conglomerates and breccias.

(b). The presence of acidic or intermediate rocks, clasts or rock fragments associated with these fine grained sediments. Ocean ridges tend to be dominated by basic rocks only, whilst hot spots may have, in addition to basic, intermediate rocks present as well. Arcs may be largely basic when youthful, but mature to produce calc-alkaline and acidic volcanic rocks. Acidic rocks fragments are associated with the cherts at Bennane Head.

(c). Whether the sediments show any signs of tectonic activity as might occur when an arc splits to form a new marginal basin i.e. aprons of mass flow deposits with much coarse sediment associated with slumped beds. These sediments can be seen at Locality 12 on Excursion 25 at Pinbain and at Locality 3 on Excursion 27 at Bennane Head. The stratigraphical associations at Pinbain are not clear as the exposure is fault bounded. Bennane Head is the critical exposure, for here is a sequence from lavas and conglomerates up into cherts, and that is the sequence one would expect where layer 2 (basalt layer of (Figure 25.3)) is overlain by sediments (layer 1 of (Figure 25.3)). So at Bennane

Head it would appear that we have a clear example of layer 1 in its stratigraphical context.

2. The lava sequence is also quite critical for the identification of the origin of the ophiolite at Ballantrae. Lavas occur in at least three quite extensive blocks, the most northerly of which is the Pinbain block. The lavas and associated sediments of this block are terminated to the SE by a major fault (the Pinbain Fault seen on Excursion 25) and to the NE the unconformably overlying Girvan clastic sequence. South of Pinbain lies the Bennane Head block, which has a sequence of cherts and shale at its top (see above) and by a major fault at its base near Games Loup. The most southerly block is found in the Mains Hill-Knockdolian region: it is terminated to the south by cherts and black shales and to the north by a major fracture. A fourth block, the Aldons block is not well known. There is no contact between the lavas and the sheeted dykes and as already discussed, there is an upper contact with strata which are superficially similar to ocean layer 1 at Bennane Head.

For the lavas which can seen on Excursions 25 and 27, there are several critical lines of evidence which allow an evaluation of their origin:

1. The abundance of breccias and conglomerates characterizes shallow water volcanic processes.
2. Massive lavas can be extruded in very deep water, but where massive flows have red tops, then they are almost certainly subaerial flows.
3. Where lavas enter the sea they may produce hyalotuff deltas, the presence of which in the volcanic pile would be a certain indication of volcanicity at or above sea level.
4. Accretionary lapilli require the volcanic ejectamenta to have been through the air column: they do not form in water alone.
5. All the above points above refer to water depth, which is obviously very significant. If a thick sequence of lava is built up from deep to shallow water, then it may have formed in an ocean island environment, possibly at the early stages in the growth of an island arc or (very unusually) a mid oceanic ridge. However if there is a thick sequence of lavas which are constantly extruded into shallow water, then we have to invoke subsidence at the same time as lava accumulation. This feature is common in island arcs, possible in unusual mid-ocean ridges and unlikely in oceanic islands.

Lavas are evidently important indicators in the evaluation of the evolution of an ophiolite, and they will be examined particularly in the light of the points made above.

The age of the Ballantrae Complex

With the Ballantrae Complex comprising both igneous and sedimentary rocks, dating has been carried out using both radiometric and palaeontological techniques. This has the advantage of being able to fit the radiometric into the palaeontological time-scale. The black shales which occur amongst the lavas, and those which are part of the olistostrome sequence, have been known for some time to contain fossils of mainly inarticulate brachiopods and graptolites. The latter are particularly useful in relative age determination and they indicate that these rocks are representative of most of the Arenig Series. Radiometric dating has been conducted on a variety of rock types using a range of methods, and with two exceptions yield ages which on the basis of world-wide data are considered to be Arenig (Figure 25.2). The exceptions are within the olistrostrome-mélange unit at Knockormal, where a garnet meta-pyroxenite has yielded an age of 576+-32Ma which is Cambrian; and the pillow lavas at Downan Point which have yielded younger ages of 468+-22Ma, which is roughly Llanvirn. The errors on either side of the mean in each of these determinations are large and, in the latter instance the age is not statistically different from age determinations from other pillow lavas to the north of Ballantrae (north of the Stinchar Valley). There is, however, an essential diffence between the lavas to the north and south of the Stinchar Valley; those to the north have a higher proportion of volcanogenic sediment. Downan Point is typified by massive pillow lavas with a minimum of volcanogenic sediment and this probably reflects the different regime. Indeed many workers would now place the Southern Uplands Fault along the Stinchar Valley to separate the pillows of Downan Point from the rest of the ophiolite.

From these radiometric ages and from the ages given by the faunas it is clear that the main part of the ophiolite was formed within the Arenig, between c.501 and c.476 Ma. a time-span of c.25 my. The age of obduction is anytime between 501–476 Ma, so it was also obducted within Arenig times. These ages imply that the oceanic crust which comprises the Ballantrae Complex was young and near to the site of its generation: wide ocean basins have oceanic crust which is often >100 Ma, since it has travelled a great distance from the ridge which created it. Thus, the diversity of the complex cannot then be explained by the great differences in its age: it has to be explained by differences within the region of its formation.

There are several papers which review the nature and origin of the Ballantrae Complex in terms of its ocean crust setting. The earliest of these are by Church and Gayer (1973), Dewey (1974), Bluck et al (1980) and Stone and Smellie (1988). The last is also a comprehensive guide to the complex with much new and significant information.

The significance of the Ballantrae Complex

The geological significance of the Ballantrae complex extends far beyond the region of Ballantrae. The presence of oceanic crust leads to a number of important conclusions, some of which have helped to unify a geological history over a considerable part of Scotland. The prime conclusion is that during the Arenig this part of Scotland was a destructive margin, where oceanic crust was being consumed. This further suggested that to the continent side of this margin there would have lain a volcanic arc; this, on the basis of information from the overlying Ordovician rocks (see Excursion 28 Locality 3) is thought to have lain to the NW. To the south there would have been an ocean.

The nature of the Ballantrae Complex is also highly significant. If it was produced in a marginal basin, as suggested here, then there would have been a major subduction zone to the south where dense, and probably old oceanic crust would have been consumed (marginal basins are at present seen to form where old oceanic crust is being consumed, as in the western Pacific). This in turn would suggest that there had been quite a long history of subduction in the Ballantrae region.

The North Atlantic region has a number of ophiolitic masses which are of this general age. They occur in Newfoundland, Scotland and Scandinavia (Dunning and Krogh 1985).

Conclusions for excursions 25–27

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The origin of the Ballantrae Complex has been debated by several workers (Dewey 1974; Church and Gayer 1973; Bluck *et al.*, 1980; Barrett *et al.*, 1981; Stone 1984). There are several lines of evidence which are critical to the understanding of the Ballantrae Complex and solving the problem of its origin:

1. The nature of the sediments which make up the top layer of the ophiolite, equivalent to layer 1 of normal ocean crust, as produced in the large ocean basins. These are seen at Pinbain (Excursion 25) and Bennane Head (Excursion 26): and the make-up of Bennane Head in particular is significant in that it differs from normal layer 1 of the crust in the following ways:

(a). Although the cherts and black shales are well bedded, both contain the remnants of volcanic activity in the form of glass shards and lithic fragments of acidic and intermediate volcanic rock. Sometimes thin breccias of volcanogenic origin are interstratified with the cherts. All of this implies that the basin in which the chert formed was close to an active acidic volcanic complex and received some of the ash blown out by the eruptions. Ash would be incorporated into layer 1 of the deep oceans at hot spots which produce ocean islands, or where the mid-ocean spreading ridge has grown sub-aerially, but in these instances most of the ash would be basic in composition.

(b). The cherts and black shales are very commonly slumped i.e. they have been deformed by submarine sliding when they were still unconsolidated. This repeated slumping, seen at Benanne Head and Pinbain, implies deposition on either some reasonably steep slope or a shallow slope which was affected by tectonic activity, setting the sediment pile in motion. This is not a characteristic feature of deep oceanic sediment: slopes are normally very shallow in the deep abyssal plains where chert sequences of this thickness are normally found. However, in the deep ocean steep slopes and instability may be generated near ridges and transform faults.

(c). The cherts and black shales are interbedded with conglomerates and breccias, some of which are boulder-bearing. Some of the clasts are well rounded and may have spent some time in fluvial transportation or have been abraded by wave activity whilst in shallow coastal regimes. When the whole sequence is mapped out both at Bennane Head and Pinbain, it can be clearly seen that the cherts and black shales pass rapidly into laterally equivalent thick sequences of rudite. This type of relationship is not characteristic of normal oceanic crust, is not usual at spreading ridges and is uncommon at transform faults. It is, in contrast, found in basins produced by arc splitting where new ocean crust is being formed. Here there are many normal faults over which substantial piles of arc-derived (acid-basic) sediments are draped. Steep surfaces upon which sediment accumulates are common, and many are rendered unstable by the continual fault activity which extends the basin. During this time there is extensive deformation of newly laid sediment.

2. The characteristics of the lavas equivalent to layer 2. There are a number of important points here:

(a). Layer 2 of oceanic crust produced at the major ocean ridges is characterized by an abundance of massive and pillowed lava; breccias and conglomerates account for <10% of the rock record. The presence of abundant breccias and tuffs throughout these lava sequences is evidence of explosive eruption of the lavas, and that in turn implies that they were continuously erupted in shallow water.

(b). A shallow water origin is also demonstrated by the presence of well-rounded lava clasts (Excursion 27); hyaloclastic deltas (which are intertidal, Excursion 25) and subaerial lava flows with reddened tops. The repetition of such features through the stratigraphic column suggests subsidence during lava extrusion which is not a common feature of ocean ridges or oceanic islands. Lavas created at oceanic ridges generally undergo subsidence after extrusion has stopped and when the lithosphere is cooling and moving away from the ridge. Ocean islands on the other hand build up from deep water to shallow, so the base of the pile should be dominated by massive and pillowed flows and the top by shallow water volcanic activity.

(c). Although there is repetition by faulting which tends apparently to thicken the section, the lavas are nevertheless very thick. Normal oceanic crust is < 1.5 km thick, and oceanic islands can produce extremely thick lavas.

(d). Breccias and lava flows of intermediate-acid type occur at the top of both the Pinbain and Bennane Head lava sequences. This type of lava is not typical of oceanic spreading centres, but is commonly found in magmatic arcs.

(e). Much work has been done on present-day oceanic lavas with a view to correlating their chemistry with the tectonic setting of their extrusion. For present-day basaltic lavas major element discriminant plots are very useful in indicating the tectonic settings in the oceanic realm. When these techniques are applied to the lavas at Ballantrae they fall into a wide variety of geochemical fields typical of oceanic islands (hot-spots), marginal basins, oceanic ridges and island arcs (Wilkinson and Cann 1974; Thirlwall and Bluck 1984). Although the validity of using these geochemical plots for ancient oceanic crust has been questioned, for recent environments of ocean crust formation those basalts formed in island arcs and marginal basins show the greatest degree of diversity in chemistry.

3. Evidence from the age dating and the obduction.

It is clear from the age determinations carried out on the ophiolite that it is of Ordovician age and was generated and abducted within the Arenig epoch. It was therefore not old crust at the time of obduction but young. Young crust tends to be thin and hotter than old, yet the metamorphic rocks at the sole of the ophiolite are required to have been buried by at least 30 km of rock (see Excursion 26). If the ophiolite were to be an arc-marginal basin assemblage which has collided with a subduction zone, then the thickness of the crust, its age and the age of obduction can easily be accounted for as shown in (Figure 26.3).

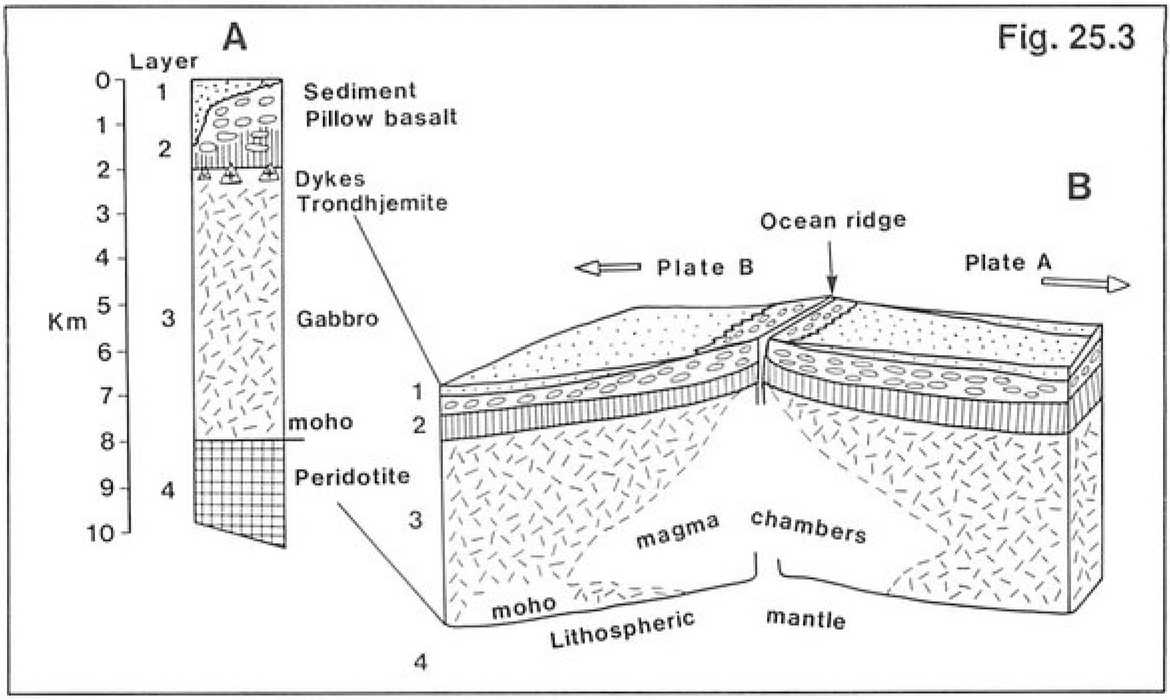
Ophiolites with similar characteristics and roughly similar age to the Ballantrae Complex have been found in Newfoundland and SW along the Appalachians (Dunning and Krogh 1985). Ophiolites of this age have also been found in Scandinavia, and their widespread occurrence at this time suggests a long destructive margin to the northern continent of Laurentia (see Introduction). In most of these instances a marginal basin origin has been proposed for the ophiolites, and we may therefore infer that the oceanic crust being consumed at that time was quite old.

There is evidence within the Ballantrae Complex and elsewhere for a long history of subduction. There is a meta-pyroxenite block within the mélange at Knockormal which has yielded an age of 576 ±32 Ma. On most time-scales this date is Cambrian, and the composition of the block suggests its protolith to be basalt. If this is so, then it is probable that oceanic crust, older than 576 Ma was somewhere being consumed. Of course this event may not have taken place at Ballantrae; the block could have been tectonically transported from some distance. However, in the dating of island arc type andesitic and rhyolitic fragments from the Southern Uplands, Kelley and Bluck, (1989) found them to have ages of 560 Ma and 630 Ma respectively— again pointing to the presence of Cambrian subduction. Dempster and Bluck (1991) have shown that an ophiolite along the Highland Border zone was thrust onto the continent at about 537 Ma., and they further discuss the implications of these ages.

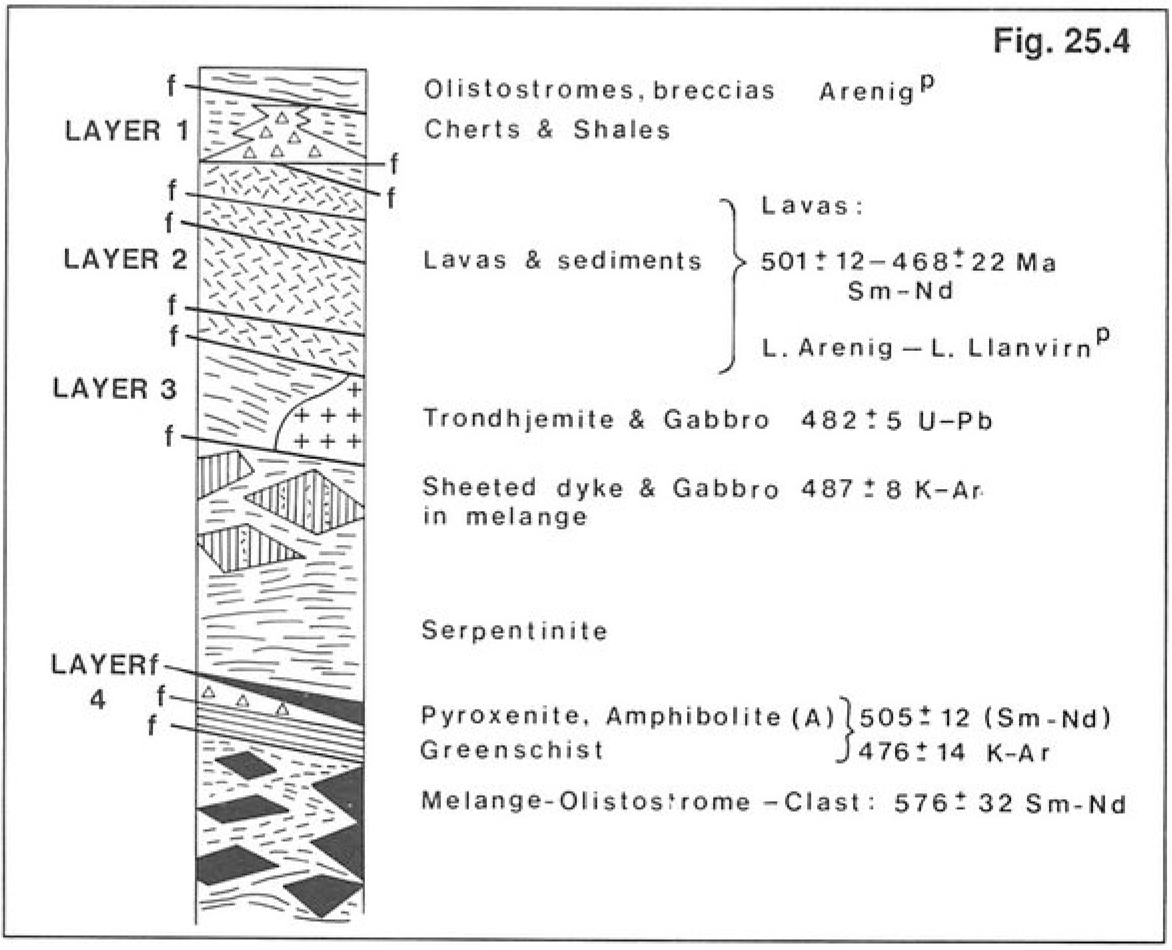
References

References for excursions 25–31

Attention should be drawn at this stage to the valuable systematic account of the Ballantrae area published by the British Geological Survey (Stone and Smellie 1988). It contains some helpful maps and photographs and should be used in conjunction with the ensuing excursion accounts.

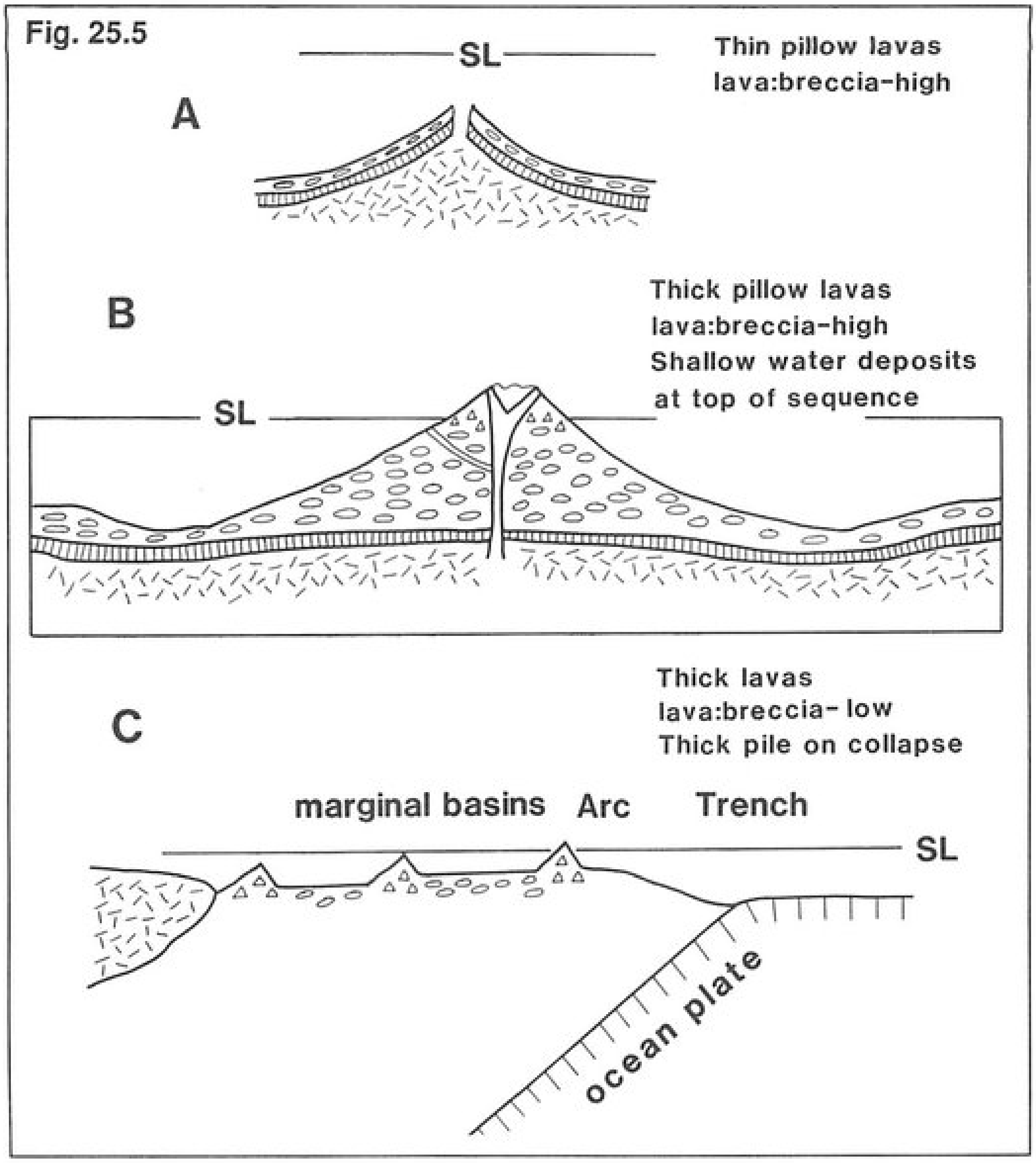


(Figure 25.3) A. Section through typical oceanic crust. B. Diagram showing how oceanic crust is created in an instance of a rapidly growing plate. The peridotite of A belongs to the lithospheric mantle of B.

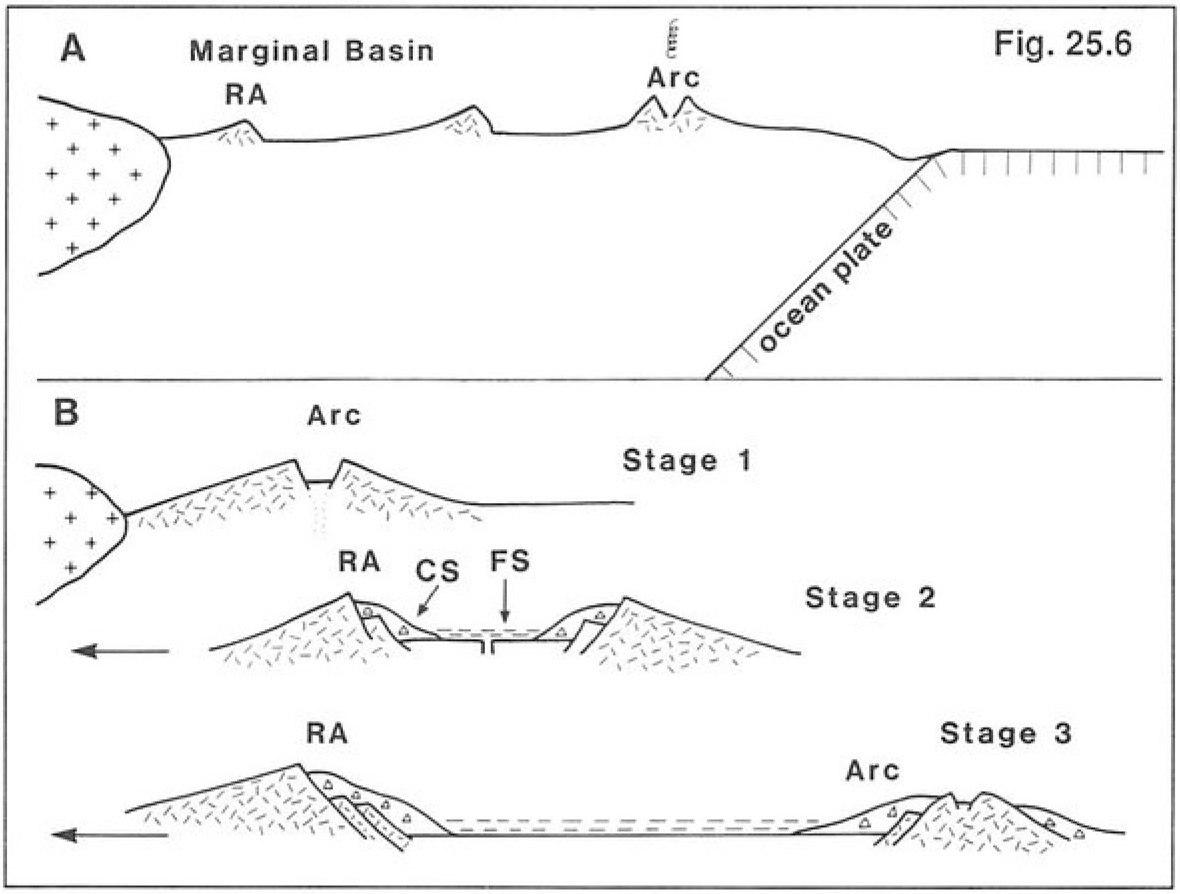


(Figure 25.4) Compound section through the Ballantrae Complex showing some of the absolute age determinations (the various methods used are shown by the conventional symbols K-Ar etc) and fossil ages (p) On the left of the section the various elements of the complex are interpreted in terms of a conventional ophiolite.

Fig. 25.5



(Figure 25.5) Diagram showing the various ways in which ophiolites form, together with some of the main characteristics which typifies each one. A. Formation at a spreading ridge; B. At an ocean seamount, C. At a marginal basin-arc. SL = sea level. The symbols are as for (Figure 25.3) and 25.4.



(Figure 25.6) Origin and development of a marginal basin. A. Section through a developed marginal basin. B. Stages in the growth of a marginal basin. Stage 1, the splitttting of an arc, Stage 2, the development of new ocean crust in the rifted arc, Stage 3, the development of a wide ocean basin. RA, remnant arc. CS = coarse sediment; FS = fine sediment.

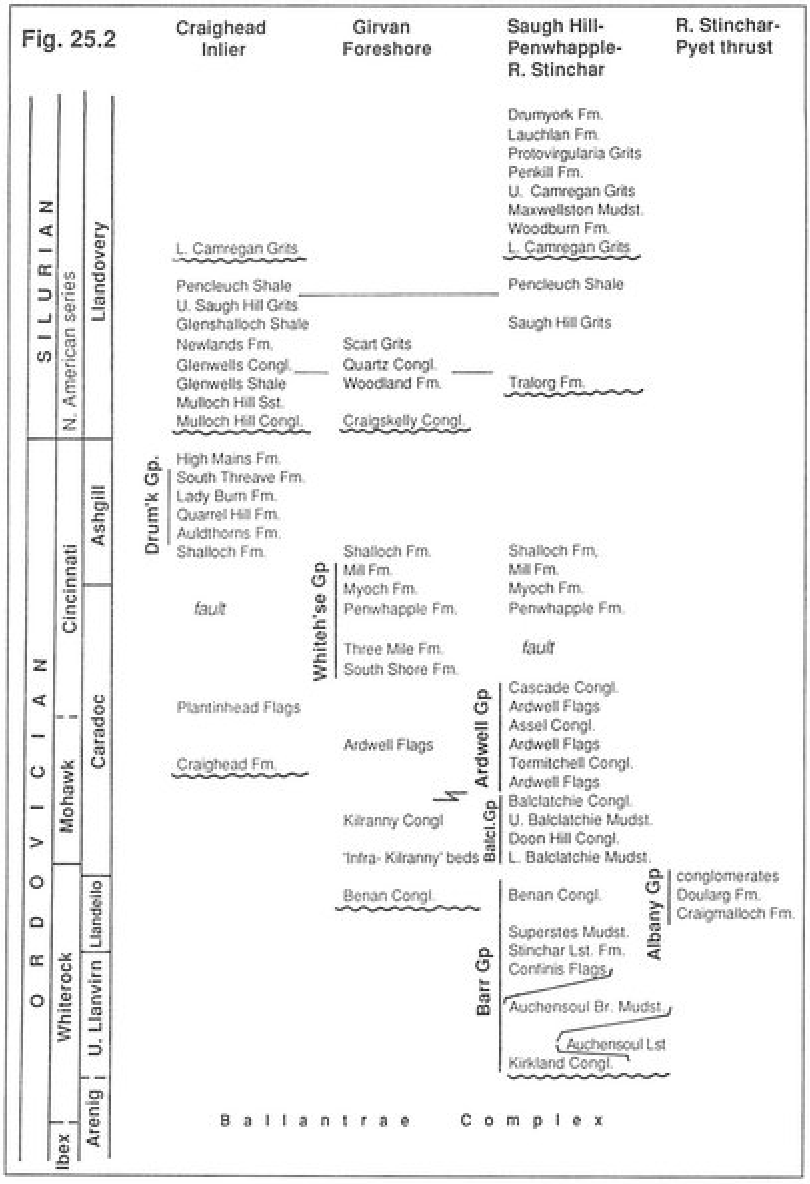


Fig. 25.2

(Figure 25.2) The Lower Palaeozoic successions in the Girvan district and their chronostratigraphical ages.

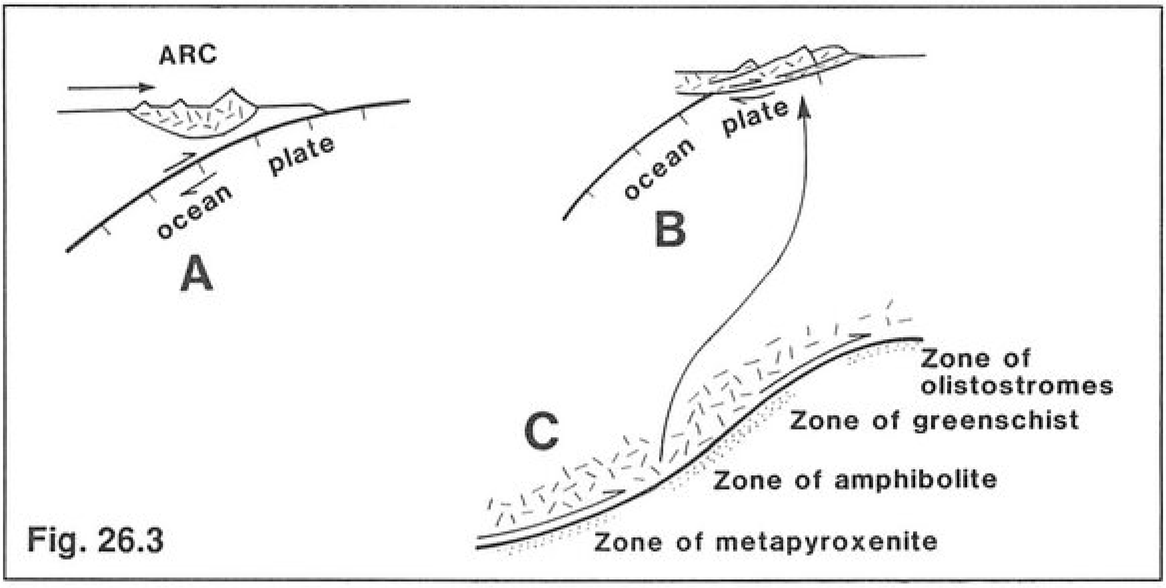


Fig. 26.3

(Figure 26.3) Possible explanation of the metamorphic sole to the ophiolite. A an arc, because of changes in the location and sense of subduction, is driven towards the source of the plate which created it. In colliding with the under-riding plate it underplates onto it the high pressure rocks belonging to this oceanic plate (B) But only fragments of this plate are *accreted to the sole of the arc (C).*